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(54) **PATH COMPUTATION IN WAVELENGTH SWITCHED OPTICAL NETWORKS**

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CPC ***H04Q 11/0066*** (2013.01); ***H04J 14/0271*** (2013.01); ***H04L 45/62*** (2013.01); *H04Q 2011/0073* (2013.01); *H04Q 2011/0083* (2013.01)

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,131,873 B2 * 3/2012 Vasseur H04L 45/04 709/203
8,396,364 B2 * 3/2013 Lee H04J 14/0256 398/25

(Continued)

FOREIGN PATENT DOCUMENTS

EP 2063585 5/2009

OTHER PUBLICATIONS

Lee, et al., "PCEP Extension for WSON Routing and Wavelength Assignment, draft-lee-pce-wson-rwa-ext-01.txt", *Network Working Group Internet Draft, IETF*, (Mar. 4, 2011), 20 pages.

(Continued)

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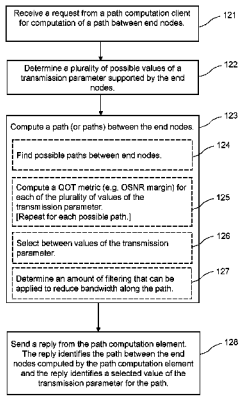
(57) **ABSTRACT**

A path computation client (PCC) can request a path computation element (PCE) to compute a path across a wavelength switched optical network. PCC sends a request which identifies end nodes. The end nodes can support a plurality of possible values of a transmission parameter, such as modulation format or Forward Error Correction (FEC) type. The PCE computes a path between the end nodes and sends a reply to the PCC. The reply identifies the path between the end nodes and identifies a selected value of the transmission parameter for the computed path. The reply can comprise a spectrum assignment for the path. The reply can be a PCE Communication Protocol (PCEP) Reply message.

14 Claims, 10 Drawing Sheets



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H04J 14/02 (2006.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,433,192	B2 *	4/2013	Frankel	H04B 10/0795 398/16
8,576,720	B2 *	11/2013	Cugini	H04L 45/00 370/238
8,644,325	B2 *	2/2014	Iovanna	H04L 45/00 370/401
8,873,948	B2 *	10/2014	Caviglia	H04J 14/0227 398/17
9,077,481	B2 *	7/2015	Sambo	
9,236,972	B2 *	1/2016	Lee	H04L 45/00
9,312,914	B2 *	4/2016	Vassilieva	H04B 3/32
9,372,830	B2 *	6/2016	Vassilieva	G06F 17/00
2006/0104199	A1 *	5/2006	Katukam	H04L 12/43 370/216
2008/0298805	A1 *	12/2008	Lee	H04J 14/0227 398/48
2009/0110395	A1 *	4/2009	Lee	H04Q 11/0062 398/48
2010/0202773	A1	8/2010	Lee et al.	
2010/0220996	A1 *	9/2010	Lee	H04J 14/0227 398/25
2011/0199939	A1 *	8/2011	Zi	H04L 45/42 370/254
2015/0043907	A1 *	2/2015	Cavaliere	H04J 14/0247 398/30
2015/0139652	A1 *	5/2015	Bottari	H04J 14/0256 398/79
2015/0256253	A1 *	9/2015	Bottari	H04J 14/0268 398/28
2015/0333824	A1 *	11/2015	Swinkels	H04J 14/0241 398/25
2015/0333862	A1 *	11/2015	Swinkels	H04J 14/0241 398/79
2016/0013861	A1 *	1/2016	Ceccarelli	H04L 43/0847 398/25

OTHER PUBLICATIONS

PCT International Search Report for PCT Counterpart Application No. PCT/EP2011/069303, (May 14, 2012), 4 pages.

Ash, et al., "Path Computation Element (PCE) Communication Protocol Generic Requirements", *Network Working Group Request for Comments: 4657, The Internet Society*, http://www.ietf.org/rfc/rfc4657.txt, (Sep. 2006), 21 pages.

Farrel, et al., "A Path Computation Element (PCE)—Based Architecture", Network Working Group Request for Comments 4655, http://www.ietf.org/rfc/rfc4655.txt, (Aug. 2006), 40 pages.

Kozicki, et al., "Distance-Adaptive Path Allocation in Elastic Optical Path Networks", *IEICE Trans. Commun.*, vol. E94-B, No. 7, (Jul. 2011), 8 pages.

Lee, et al., "PCEP Extensions for WSON Impairments", *Network Working Group Internet Draft, Internet Engineering Task Force (IETF)*, draft-lee-pce-wson-impairments-02.txt, (Jul. 7, 2011), 19 pages.

Margaria, et al., "PCEP extensions for GMPLS", *Network Working Group Internet-Draft, Internet Engineering Task Force (IETF)*, draft-ietf-pce-gmpls-pcep-extensions-02, (Mar. 11, 2011), 39 pages.

Otani, et al., "Generalized Labels for Lambda-Switch-Capable (LSC) Label Switching Routers", *Internet Engineering Task Force (IETF) Request for Comments: 6205*, http://datatracker.ietf.org/doc/rfc6205/, (Mar. 2011), 15 pages.

Paolucci, et al., "Experimental Demonstration of Impairment-Aware PCE for Multi-Bit-Rate WSONs", *J. Opt. Commun.* Netw./vol. 3, No. 8, (Aug. 2011), 10 pages.

Sambo, et al., "Candidate Paths for Impairment-Aware PCE in 10-100 Gb/s Optical Networks", *IEEE Communications Letters*, vol. 15, No. 8, (Aug. 2011), 3 pages.

Vasseur, JP , et al., "Path Computation Element (PCE) Communication Protocol (PCEP)", *Network Working Group Request for Comments: 5440, Internet Engineering Task Force, IETF*, https://datatracker.ietf.org/doc/rfc5440/, (Mar. 2009), 87 pages.

International Preliminary Report on Patentability, Application No. PCT/EP2011/069303, dated Mar. 20, 2014, 6 pages.

First Office Action, Chinese Application No. 201180073316.8, dated Mar. 28, 2016, 20 pages.

* cited by examiner

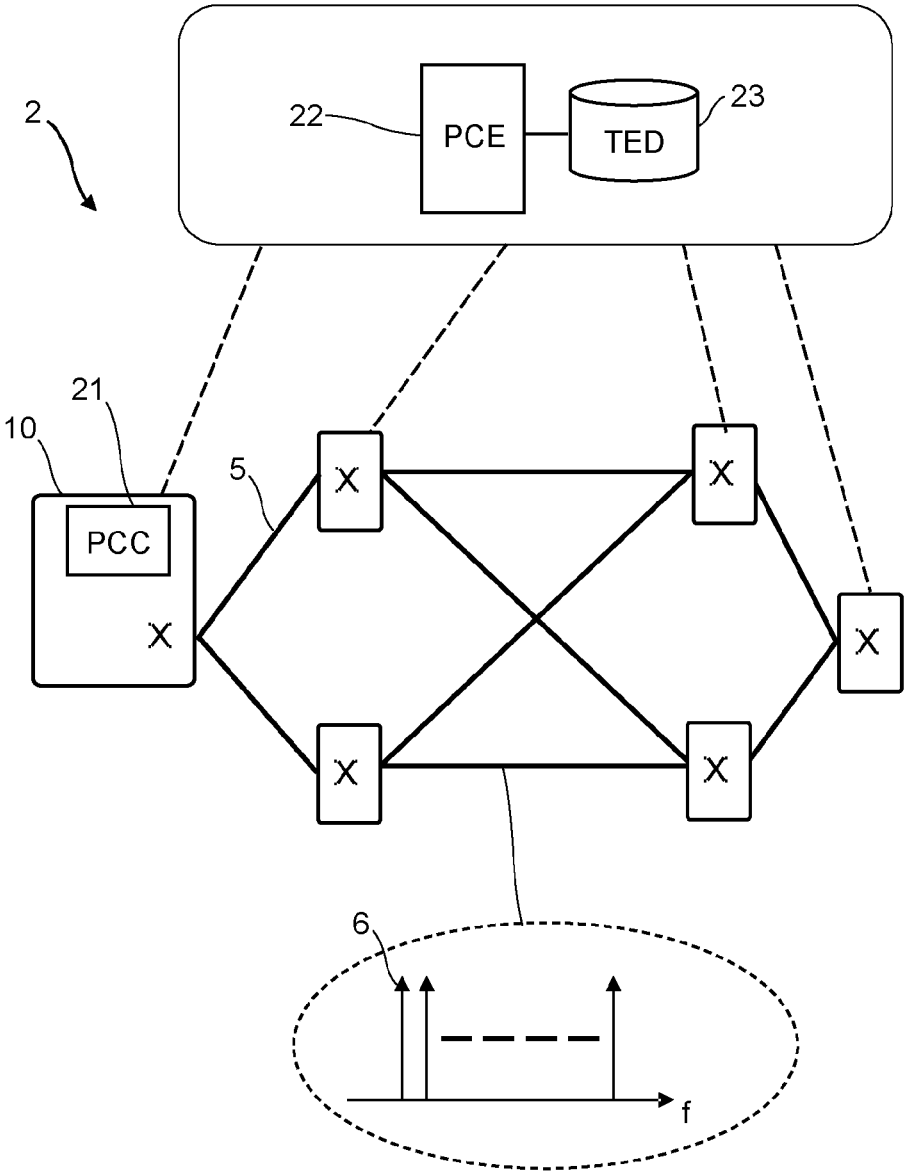

Fig. 1

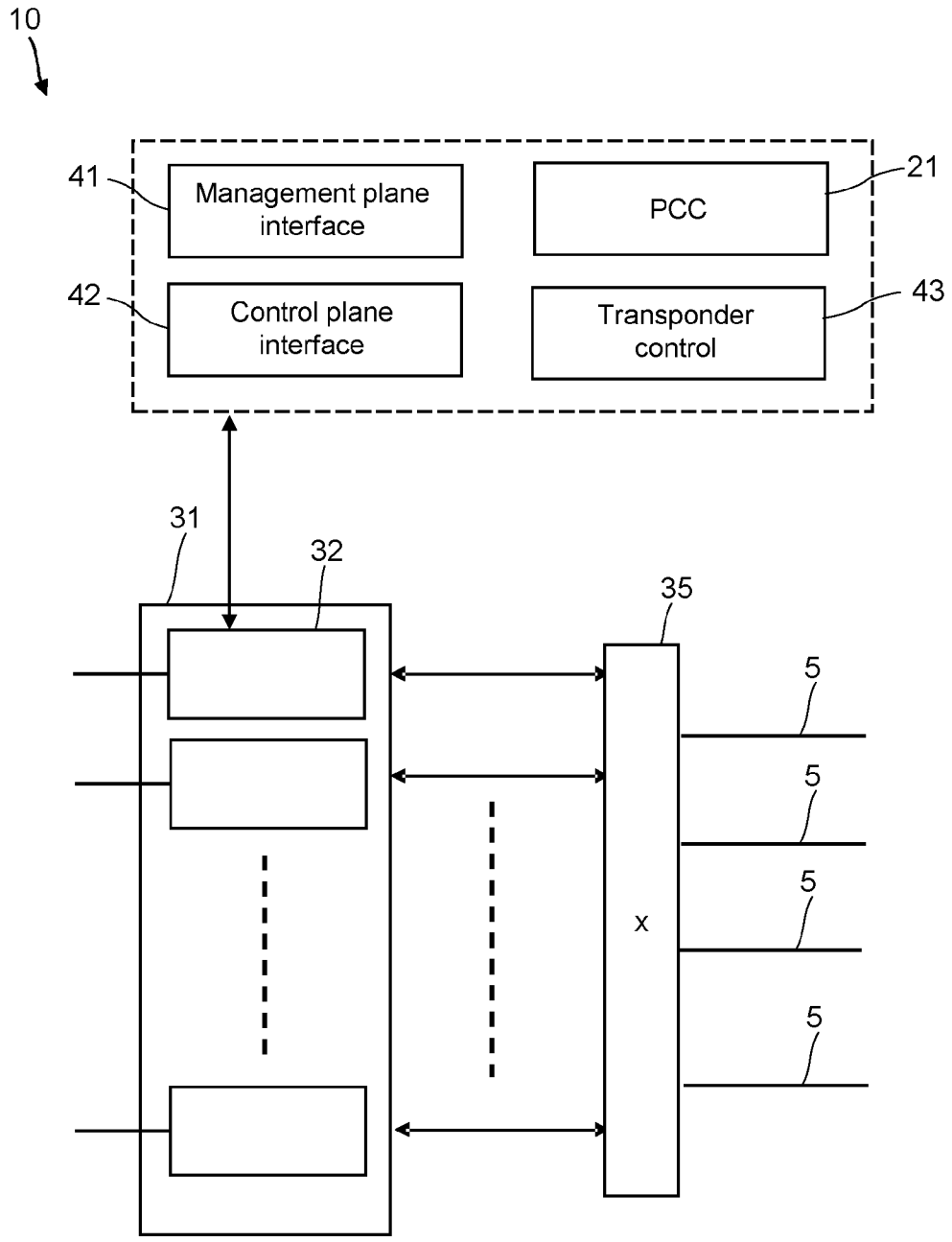
10
41
Management plane interface
PCC
21
42
Control plane interface
Transponder control
43
31
32
35
5
5
5
5
x

Fig. 2

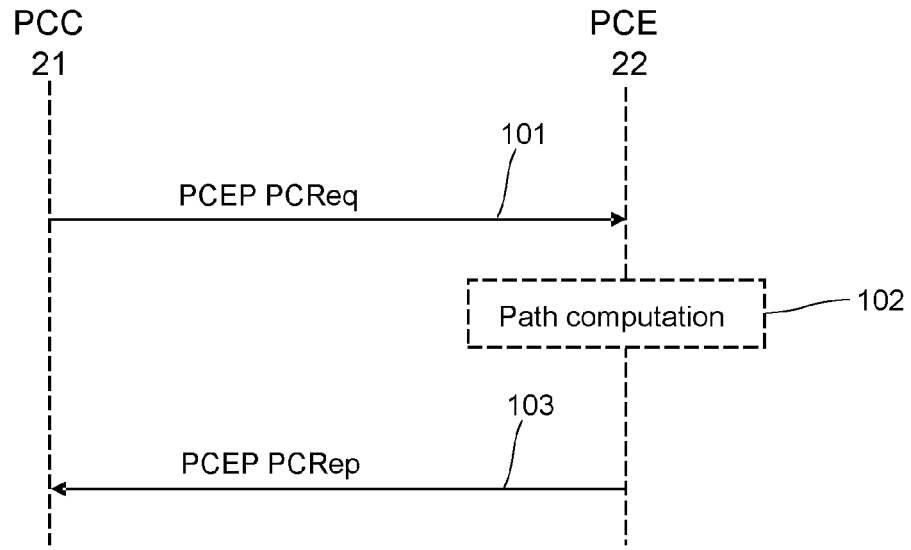
PCC
21
PCE
22
101
PCEP PCReq
Path computation
102
103
PCEP PCRep

Fig. 3

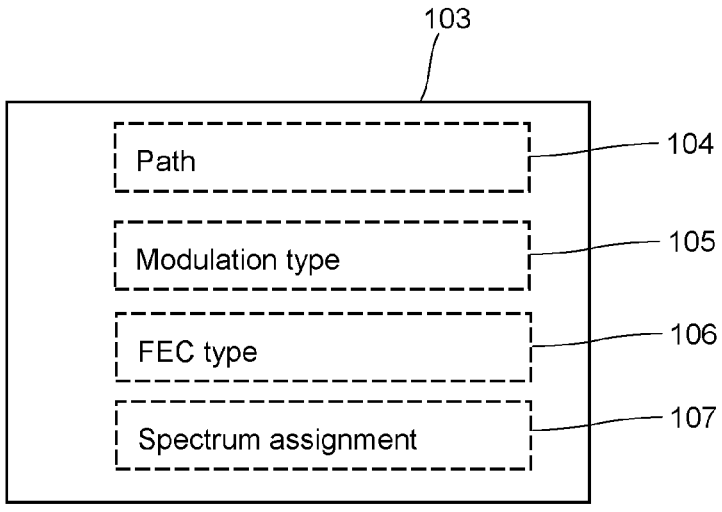
103
Path
104
Modulation type
105
FEC type
106
Spectrum assignment
107

Fig. 4

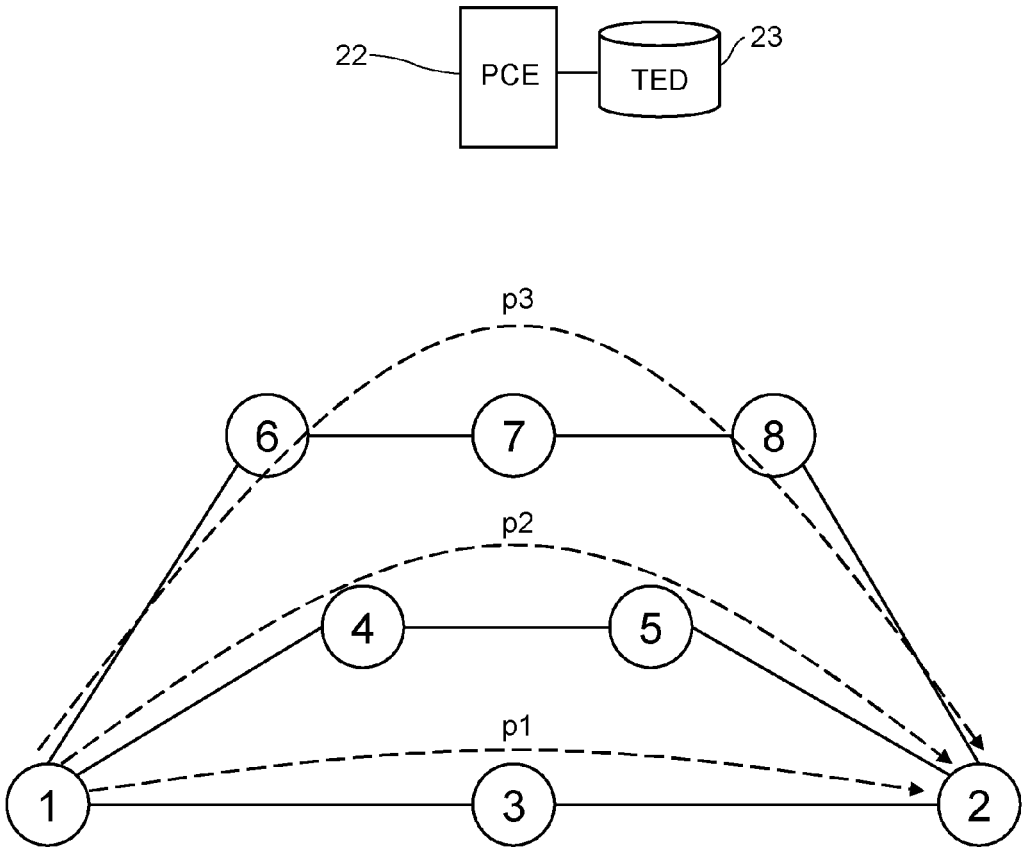

Fig. 5

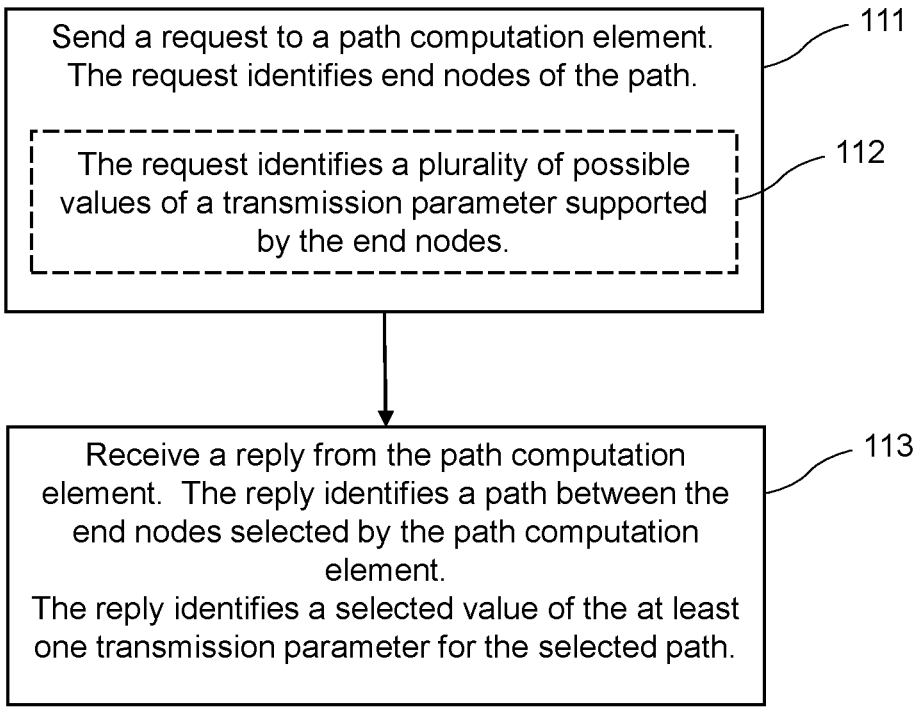
Send a request to a path computation element. The request identifies end nodes of the path.
111
The request identifies a plurality of possible values of a transmission parameter supported by the end nodes.
112
Receive a reply from the path computation element. The reply identifies a path between the end nodes selected by the path computation element.
The reply identifies a selected value of the at least one transmission parameter for the selected path.
113

Fig. 6

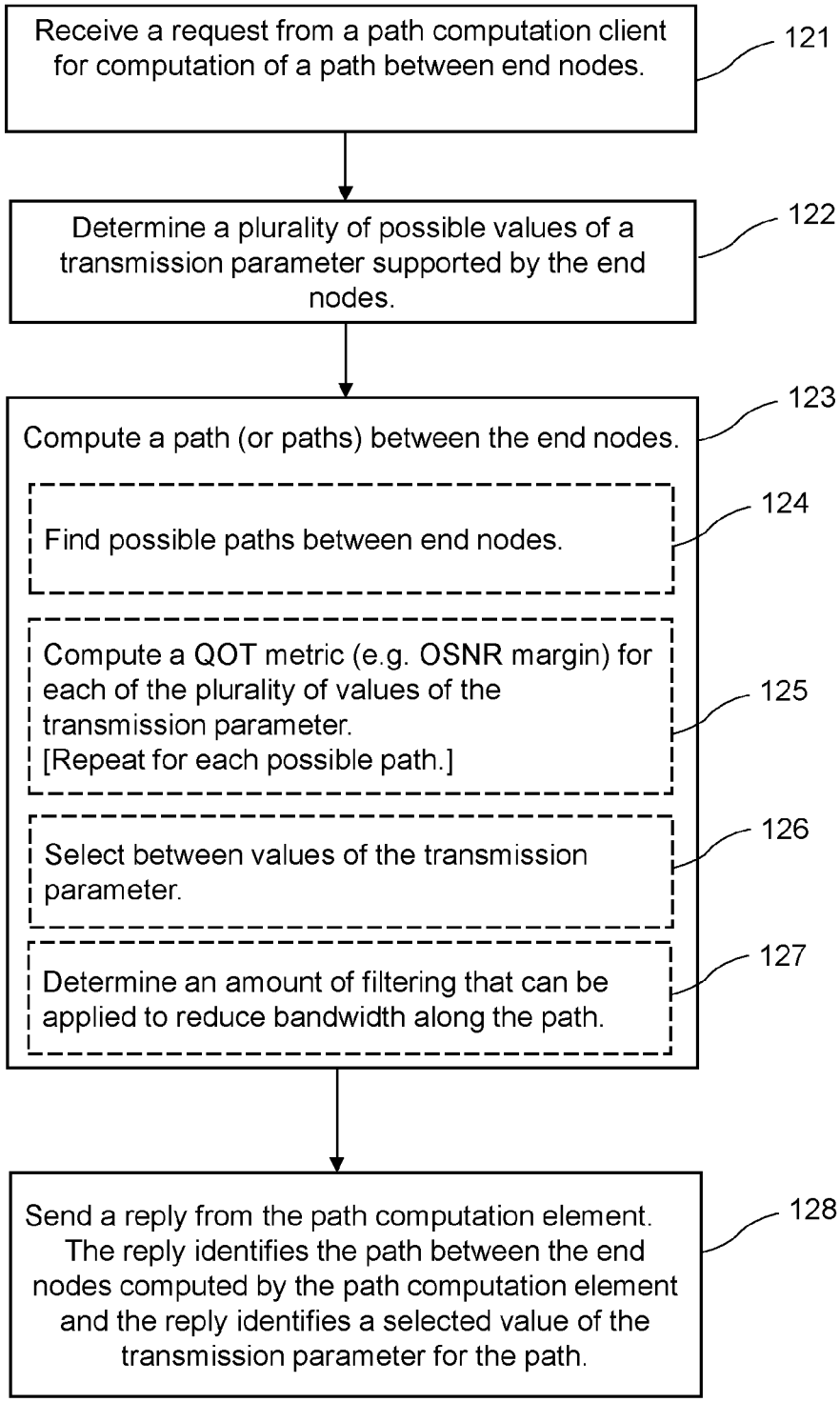
Receive a request from a path computation client for computation of a path between end nodes.
121
Determine a plurality of possible values of a transmission parameter supported by the end nodes.
122
Compute a path (or paths) between the end nodes.
123
Find possible paths between end nodes.
124
Compute a QOT metric (e.g. OSNR margin) for each of the plurality of values of the transmission parameter.
[Repeat for each possible path.]
125
Select between values of the transmission parameter.
126
Determine an amount of filtering that can be applied to reduce bandwidth along the path.
127
Send a reply from the path computation element. The reply identifies the path between the end nodes computed by the path computation element and the reply identifies a selected value of the transmission parameter for the path.
128

Fig. 7

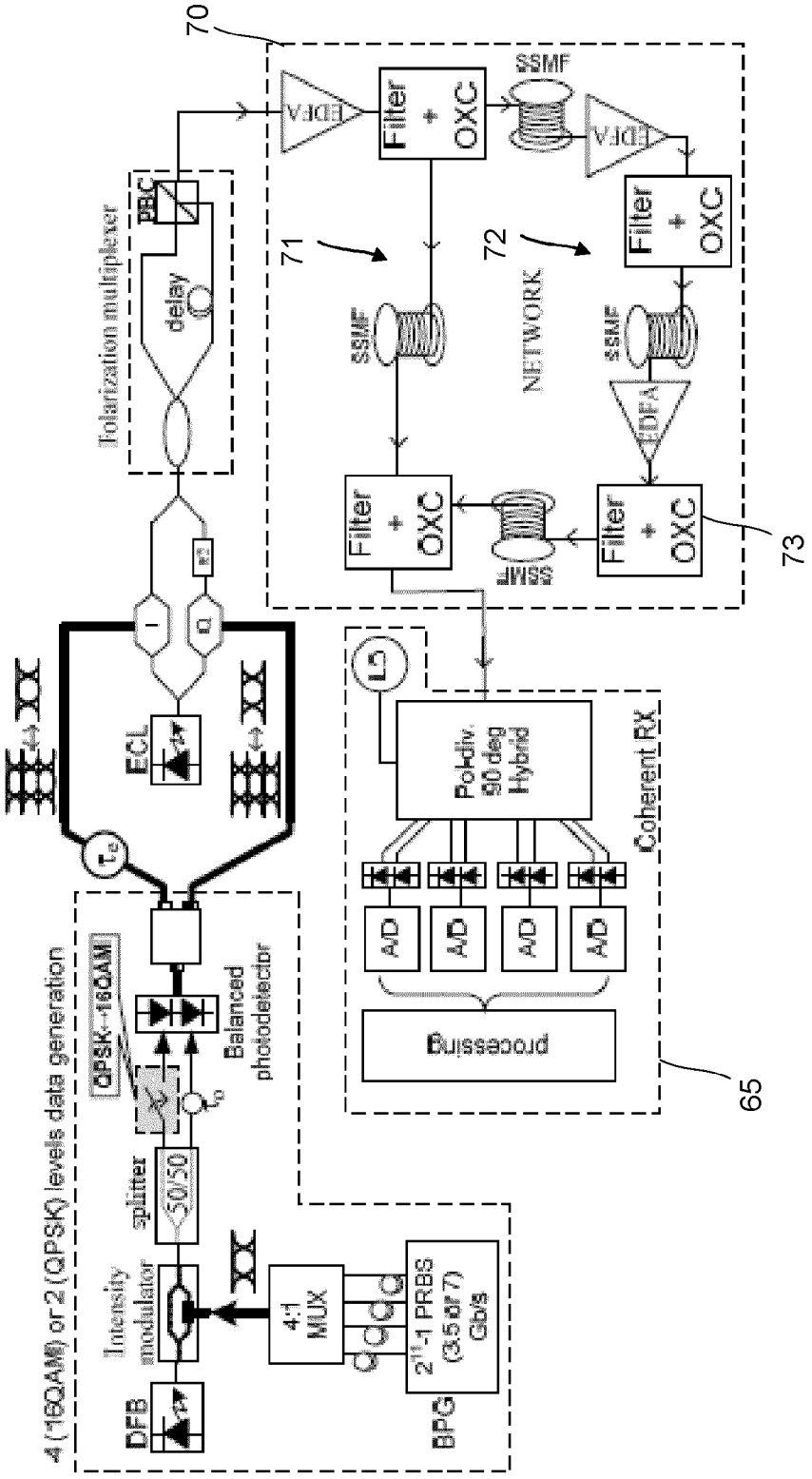
70
EDFA
Filter + OXC
SSMF
EDFA
Filter + OXC
71
72
NETWORK
SSMF
SSMF
EDFA
Filter + OXC
SSMF
Filter + OXC
73
Polarization multiplexer
PBC
delay
I
Q
ECL
Pol-div. 90 deg Hybrid
LO
A/D
A/D
A/D
A/D
processing
Coherent RX
65
QPSK→16QAM
Balanced photodetector
splitter
50/50
Intensity modulator
DFB
4:1 MUX
2^{11}-1 PRBS (3.5 of 7) Gb/s
BPG
4 (16QAM) or 2 (QPSK) levels data generation

Fig. 8

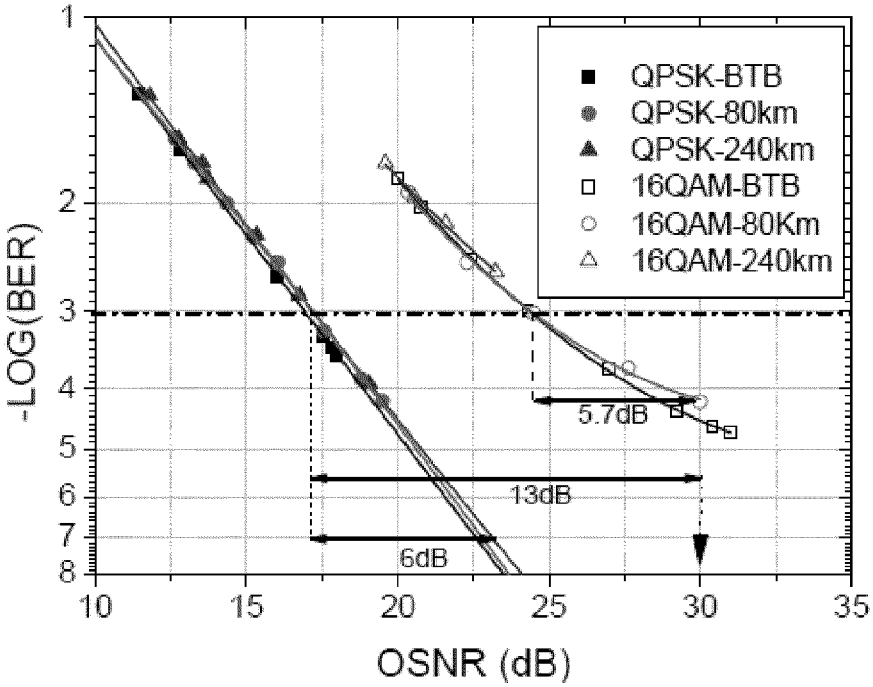
QPSK-BTB
QPSK-80km
QPSK-240km
16QAM-BTB
16QAM-80Km
16QAM-240km
5.7dB
13dB
6dB
-LOG(BER)
OSNR (dB)

Fig. 9

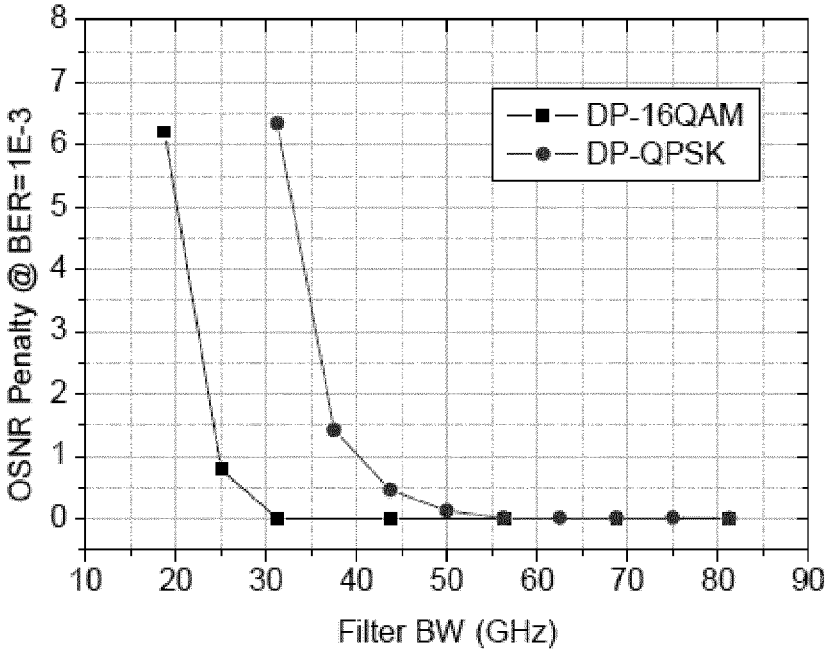
DP-16QAM
DP-QPSK
OSNR Penalty @ BER=1E-3
Filter BW (GHz)

Fig. 10

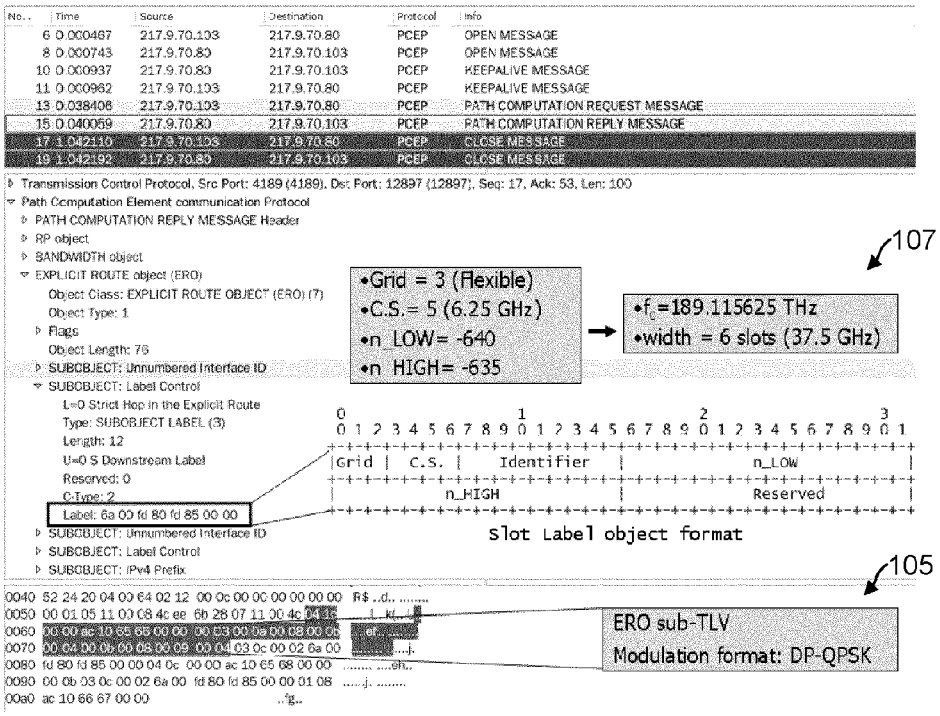
No.. Time Source Destination Protocol Info
6 0.000467 217.9.70.103 217.9.70.80 PCEP OPEN MESSAGE
8 0.000743 217.9.70.80 217.9.70.103 PCEP OPEN MESSAGE
10 0.000937 217.9.70.80 217.9.70.103 PCEP KEEPALIVE MESSAGE
11 0.000962 217.9.70.103 217.9.70.80 PCEP KEEPALIVE MESSAGE
13 0.038408 217.9.70.103 217.9.70.80 PCEP PATH COMPUTATION REQUEST MESSAGE
15 0.040059 217.9.70.80 217.9.70.103 PCEP PATH COMPUTATION REPLY MESSAGE
17 1.042110 217.9.70.103 217.9.70.80 PCEP CLOSE MESSAGE
19 1.042192 217.9.70.80 217.9.70.103 PCEP CLOSE MESSAGE
Transmission Control Protocol, Src Port: 4189 (4189), Dst Port: 12897 (12897), Seq: 17, Ack: 53, Len: 100
Path Computation Element communication Protocol
PATH COMPUTATION REPLY MESSAGE Header
RP object
BANDWIDTH object
EXPLICIT ROUTE object (ERO)
Object Class: EXPLICIT ROUTE OBJECT (ERO) (7)
Object Type: 1
Flags
Object Length: 76
SUBOBJECT: Unnumbered Interface ID
SUBOBJECT: Label Control
L=0 Strict Hop in the Explicit Route
Type: SUBOBJECT LABEL (3)
Length: 12
U=0 S Downstream Label
Reserved: 0
C-Type: 2
Label: 6a 00 fd 80 fd 85 00 00
SUBOBJECT: Unnumbered Interface ID
SUBOBJECT: Label Control
SUBOBJECT: IPv4 Prefix
•Grid = 3 (Flexible)
•C.S.= 5 (6.25 GHz)
•n LOW= -640
•n HIGH= -635
•f_c =189.115625 THz
•width = 6 slots (37.5 GHz)
107
0 1 2 3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
Grid | C.S. | Identifier | n_LOW
n_HIGH | Reserved
Slot Label object format
105
0040 52 24 20 04 00 64 02 12 00 0c 00 00 00 00 00 00 R$ ..d. ....
0050 00 01 05 11 07 08 4c ee 6b 28 07 11 00 4c
0060 00 00 ac 10 65 65 00 00 00 53 00 8a 00 08 00 06 ....ee... .S......
0070 00 04 00 0b 00 08 00 09 00 04 03 0c 00 02 6a 00 ....j.
0080 fd 80 fd 85 00 00 04 0c 00 00 ac 10 65 68 00 00 ....eh..
0090 00 0b 03 0c 00 02 6a 00 fd 80 fd 85 00 00 01 08 ....
00a0 ac 10 66 67 00 00 ..fg..
ERO sub-TLV
Modulation format: DP-QPSK

Fig. 11

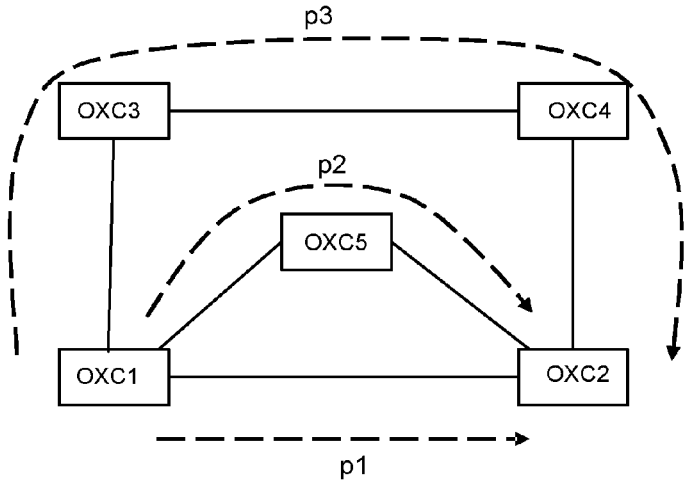
p3
OXC3
OXC4
p2
OXC5
OXC1
OXC2
p1

Fig. 12

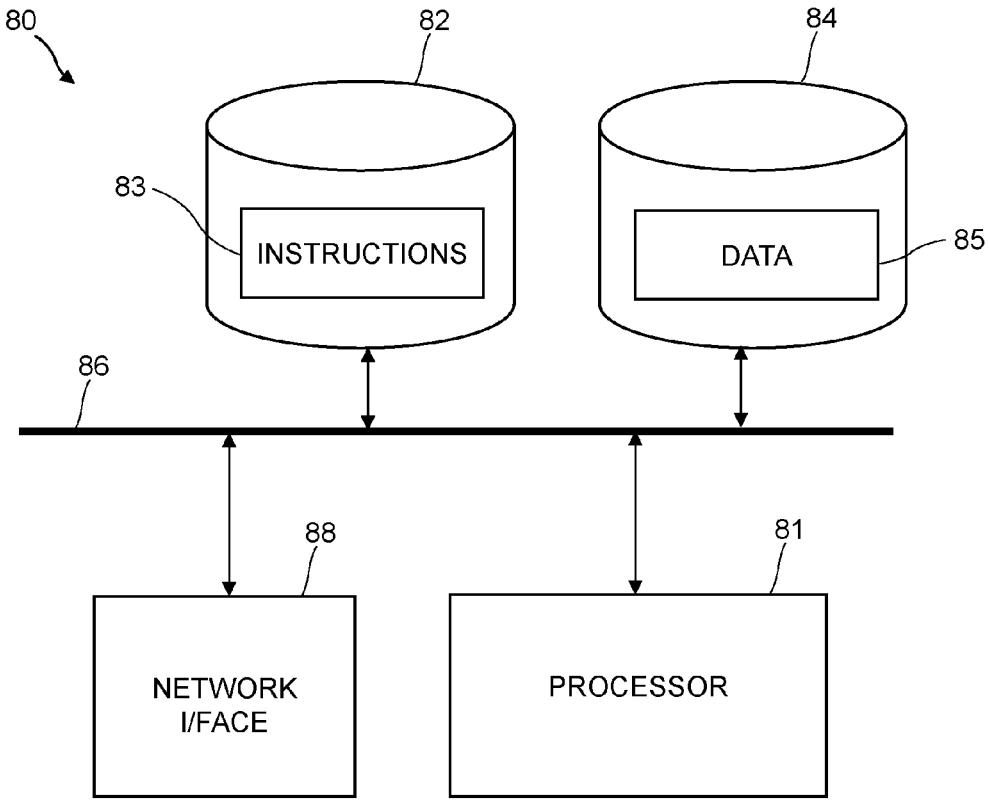
80
82
84
83
INSTRUCTIONS
DATA
85
86
88
81
NETWORK I/FACE
PROCESSOR

Fig. 13

PATH COMPUTATION IN WAVELENGTH SWITCHED OPTICAL NETWORKS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a National stage of International Application No. PCT/EP2011/069303, filed Nov. 3, 2011, which claims priority to European Application No. 11180516.4, filed Sep. 8, 2011, which are hereby incorporated by reference.

TECHNICAL FIELD

This invention relates to computation of a path in a wavelength switched optical network (WSON), to apparatus for requesting the path computation and to apparatus for performing the path computation.

BACKGROUND

A Wavelength Switched Optical Network (WSON) supports end-to-end optical paths, called lightpaths, between nodes requiring connection in the network. WSONs can be deployed across large areas and optical paths can be routed, if possible, with minimal electrical regeneration. Traffic is optically switched at intermediate nodes by Wavelength Selective Switches (WSS). Links in a WSON are operated in a Wavelength Division Multiplexed (WDM) manner, and carry traffic at a plurality of different wavelengths. When establishing a path between end nodes, the path may be assigned a particular wavelength for the entire end-to-end path between end nodes, or the path may be assigned different wavelengths on different legs of the path between end nodes if wavelength conversion is supported.

A Path Computation Element (PCE) has been defined as an entity (component, application, or network node) that is capable of computing a network path or route based on a network graph and applying computational constraints. A Path Computation Client (PCC) is a client application requesting a path computation to be performed by the PCE. The PCC and PCE communicate through the PCE communication Protocol (PCEP). PCEP operations have been defined to enable effective PCE-based path computations and, in turn, the effective use of network resources. A PCE-based architecture is described in Internet Engineering Task Force (IETF) document RFC 4655 and the PCE communication Protocol is described in RFC 4657.

In a WSON, the Path Computation Client can be an end node which wishes to establish a path across the WSON. The PCE can be located anywhere within the network, and may be within an optical switching element, a Network Management System (NMS) or Operational Support System (OSS), or may be an independent network server.

Transponders in currently deployed nodes typically adopt unique, or statically configured, transmission technologies, e.g. a unique supported modulation format per transponder.

Specific PCEP operations have been defined for WSONs. They include, for example, the capability to enable impairment-validation and routing and wavelength assignment. US 2010/0220996A1 and "PCEP Extensions for WSON Routing and Wavelength Assignment", draft-lee-pce-wson-rwa-ext-01.txt, March 2011, http://tools.ietf.org/html/draft-lee-pce-wson-rwa-ext-01 describe PCEP signalling in a WSON. These PCEP operations can send a transmission parameter such as a modulation format or a FEC type from a PCC to a PCE. These are simply used as inputs, or constraints, by the PCE and the PCE will attempt to calculate a path between the end nodes which meets the constraints.

SUMMARY

An aspect of the present invention provides a method of servicing a request for path computation at a path computation element of a wavelength switched optical network. The method comprises receiving a request from a path computation client for computation of a path between end nodes. The method comprises determining a plurality of possible values of a transmission parameter supported by the end nodes. The method comprises computing a path between the end nodes. The computing comprises selecting one of the values of the transmission parameter. The method comprises sending a reply to the path computation client. The reply identifies the path between the end nodes and the reply identifies the selected value of the transmission parameter for the computed path.

Another aspect provides method of requesting computation of a path at a path computation client of a wavelength switched optical network. The method comprises sending a request to a path computation element for computation of a path between end nodes, wherein the end nodes support a plurality of possible values of a transmission parameter. The method comprises receiving a reply from the path computation element. The reply identifies a path between the end nodes computed by the path computation element and the reply identifies a selected value of the transmission parameter for the path.

A path computation client (PCC) is provided with a value of at least one transmission parameter obtained as an outcome of the path computation performed by the path computation element (PCE). The selected value of the one or more transmission parameter can be communicated to the PCC in a PCE Communication Protocol (PCEP) Reply message.

The transmission parameter can be modulation format. Some possible values of the modulation format transmission parameter are Dual Polarisation-Quadrature Phase Shift Keying (DP-QPSK) and Dual Polarisation-16 Quadrature Amplitude Modulation (DP-16 QAM). Other values can be used. The configuration of a different modulation format typically requires the reservation along the path of a different amount of spectrum resources. This can also cause a different performance, in terms of the supported optical reach. In general, the more efficient a modulation format is in terms of bandwidth, the more critical the optical reach.

Another possible transmission parameter is Forward Error Correction (FEC) type. Different FEC types require a different amount of data overhead, i.e., a different line-rate and different required spectrum resources. However, different FEC types also enable a different level of quality of transmission (e.g., acceptable Bit Error Rate pre-FEC), with direct implications in the optical reach.

The method is particularly suitable for WSONs with flexible transponders where transmission parameters (e.g. modulation format and/or FEC type) can be dynamically configured according to the required optical reach and to the specific link or path impairment characteristics.

An advantage of an embodiment is that it is possible to determine an adequate quality of transmission while using a value of a transmission parameter which is more efficient, for example, in terms of bandwidth usage. This allows a more optimal use of spectrum resources in a flexible wavelength switched optical network.

The PCE can determine a result to meet an objective function, such as minimisation of the required spectrum resources given a certain quality of transmission target. The objective function can be statically configured at the PCE. Alternatively, the objective function can be communicated to the PCE within the PCEP Request.

The value of the transmission parameter (e.g. optimal modulation format and FEC type) communicated to the PCC is applied in nodes of the WSON to establish the path.

The PCE can be located anywhere within the network, and may be within an optical switching element, a Network Management System (NMS) or Operational Support System (OSS), or may be an independent network server.

The optical network can use optical orthogonal frequency division multiplexing (OFDM) or single carrier transmission technologies.

Further aspects of the invention provide apparatus for performing any of the described or claimed steps of the methods.

An aspect of the invention provides a path computation element (PCE) for use in a wavelength switched optical network. The PCE comprises an interface for communicating with a path computation client (PCC). The PCE comprises a processor arranged to receive a request from the path computation client via the interface for computation of a path between end nodes, the end nodes supporting a plurality of possible values of a transmission parameter. The processor is arranged to determine a plurality of possible values of a transmission parameter supported by the end nodes. The processor is arranged to compute a path between the end nodes, wherein the computing of a path comprises selecting one of the values of the transmission parameter. The processor is arranged to send a reply via the interface. The reply identifies the path between the end nodes selected by the path computation element and the reply identifies a selected value of the transmission parameter for the path.

An aspect of the invention provides a path computation client (PCC) for use in a wavelength switched optical network. The PCC comprises an interface for communicating with a path computation element (PCE). The PCC comprises a processor arranged to send a request for computation of a path to the path computation element via the interface. The request identifies end nodes of the path. The end nodes support a plurality of possible values of a transmission parameter. The processor is arranged to receive a reply from the path computation element. The reply identifies a path between the end nodes selected by the path computation element and the reply identifies a selected value of the at least one transmission parameter for the path.

The functionality described here can be implemented in hardware, software executed by a processing apparatus, or by a combination of hardware and software. The processing apparatus can comprise a computer, a processor, a state machine, a logic array or any other suitable processing apparatus. The processing apparatus can be a general-purpose processor which executes software to cause the general-purpose processor to perform the required tasks, or the processing apparatus can be dedicated to perform the required functions. Another aspect of the invention provides machine-readable instructions (software) which, when executed by a processor, perform any of the described methods. The machine-readable instructions may be stored on an electronic memory device, hard disk, optical disk or other machine-readable storage medium. The machine-readable instructions can be downloaded to the storage medium via a network connection.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be described, by way of example only, with reference to the accompanying drawings in which:

FIG. **1** shows a Wavelength Switched Optical Network (WSON);

FIG. **2** shows a node of the WSON of FIG. **1**;

FIG. **3** shows PCEP communication between a PCC and a PCE;

FIG. **4** shows a message used in FIG. **3**;

FIG. **5** shows an example topology of a WSON;

FIG. **6** shows a method performed at a PCC;

FIG. **7** shows a method performed at a PCE;

FIG. **8** shows a testbed WSON;

FIGS. **9** and **10** shows data obtained using the testbed of FIG. **8**;

FIG. **11** shows communication between nodes of the testbed;

FIG. **12** shows another example topology of a WSON as a testbed;

FIG. **13** shows a computer system for implementing one of the path computation entities.

DETAILED DESCRIPTION

FIG. **1** shows an example optical transmission network **2** with nodes **10**, which can also be called network elements. Optical transmission links **5** connect nodes **10**. Traffic is carried on links **5** by wavelength channels **6**, called lambdas. Connections or lightpaths are established in the network **2**. Each lightpath is established between a pair (or more) of nodes **10** of the network **2**. The terms "connection" and "lightpath" will be used interchangeably. A lightpath can pass via intermediate nodes. Each node has network interfaces for optically transmitting traffic on lambdas and for optically receiving traffic on lambdas. A node **10** connects to multiple links **5** and can comprise a flexible wavelength selective switch (WSS), e.g. a bandwidth-variable optical cross connect (BV-OXC). At a node **10**, traffic is received at a network interface on a lambda of an ingress link **5**, the traffic is forwarded to a required egress network interface, and is transmitted on a lambda of an egress link **5**. A node **10** can forward traffic to other nodes **10** of network **2**, or can add traffic received from other nodes not forming part of network **2**, or drop traffic to other nodes not forming part of network **2**.

The network **2** also comprises entities called a Path Computation Client (PCC) **21** and a Path Computation Element (PCE) **22**. A Path Computation Client (PCC) submits a request to the PCE to compute a path. The PCE **22** services requests from PCCs. The PCE is arranged to compute a routing between end nodes and replies to the PCC with the selected path. Advantageously the PCE can also perform spectrum assignment and Impairment Validation (IV) for the requested lightpath. The combined functions of Routing and Spectrum Assignment are called (RSA). A PCE which performs combined Routing and Spectrum Assignment and Impairment Validation will be abbreviated to IV&RSA. The PCE can use a Traffic Engineering Database (TED) **23**. The TED **23** can store information about spectrum resource availability (e.g. reservable frequency slots) to help the PCE select resources which are available. Information to verify the optical feasibility of a lightpath in an impairment aware PCE can also be stored in the TED **23**, or in another database accessible by the PCE **22**.

The Path Computation Engine (PCE) **22** can be centralised at a node of the network, or the functionality can be distributed among a plurality of nodes of the network. Similarly, the TED can be centralised or distributed. The PCE **22** can form part of the Network Management System (NMS). The PCC **21** can be located at a node **10**, as shown in FIG. **1**, but can be located at any part of the network **2**.

FIG. **2** shows an example form of one of the end nodes **10** in the optical transmission network **2** of FIG. **1**. An optical interface **31** comprises a set of transponders **32**. A transponder **32** is arranged to modulate an optical carrier signal with data using one of a range of possible modulation formats. The operating wavelength of the transponder **32** can be configured from a range of possible wavelengths. A variable bandwidth optical cross connect (BV-OXC) **35** multiplexes a set of different wavelength signals in the transmit direction and demultiplexes a set of wavelength signals in the receive direction, according to their spectrum occupation. A BV-OXC can handle a variable amount of bandwidth per channel, e.g. 25 GHz bandwidth for channel **1**, 75 GHz for an adjacent channel **2**, etc. The variable bandwidth optical cross connect (BV-OXC) **35** can also switch through traffic between links **5** in the optical domain. Bi-directional operation can be supported by separate lambdas for forward and reverse transmission directions. Advantageously, separate links **5** are used for each transmission direction. Transponders may support transmission or reception at one or more bitrates, such as 2.5 Gb/s, 10 Gb/s, 40 Gb/s, 100 Gb/s 200 Gb/s. Future systems may use higher bitrates. Transponders may support transmission or reception using one or more modulation formats, such as On-Off Keying (OOK) or a phase modulation format such as Differential Quadrature Phase Shift Keying (DQPSK), Dual Polarisation-Quadrature Phase Shift Keying (DP-QPSK), Quadrature Amplitude Modulation (DP-QAM) and Dual Polarisation-Quadrature Amplitude Modulation (DP-QAM). In a flexible WSON, the transponders **32** are not constrained to a fixed grid of wavelength channels. Instead, a transponder can be assigned a number of frequency slots from a flexible grid. In this way, neighbouring traffic flows (channels) along an optical link **5** can have different bandwidths. The node **10** can have a management plane interface **41** and a control plane interface **42**. Control plane signalling, such as RSVP-TE signalling, can be sent between nodes to reserve resources and establish lightpaths. A transponder control module **43** controls the configuration of a transponder **32**, e.g. wavelength, bandwidth, modulation format. The transponder control module **43** communicates with the PCC **21** and the management plane interface **41** and/or the control plane interface **42** to establish values of transmission parameters to be used by the transponder **32**.

In a network where nodes can selectively communicate at 100 Gb/s using a DP-16 QAM modulation scheme and at 100 Gb/s using a DP-QPSK modulation scheme, there are different spectrum occupations for these two schemes. DP-16 QAM halves the required spectrum with respect to DP-QPSK. Flexible WSONs can provide an advantage in terms of occupied spectrum resources by efficiently exploiting both: (i) flexible transponders operating with configurable advanced modulation formats and (ii) flexible optical cross-connects (OXCs) with configurable frequency slots per output port. Modulation format and flexible OXCs can be dynamically configured, according to the required optical reach, in order to minimise the spectrum utilisation.

FIG. **3** shows PCEP communication between PCC **21** and PCE **22**. The communication comprises the PCC sending a PCEP Request message **101** to the PCE **22**. PCE **22** computes **102** a path based on information received in the Request message **101**. PCE **22** can also use other information, such as impairment information and information about available wavelength channels. PCE **22** then sends a PCEP Reply message **103** to the PCC **21**.

Advantageously, the PCEP Request message identifies values of a transmission parameter supported by the end nodes of the requested path. Alternatively, other techniques could be adopted to provide this information to the PCE **22**, such as out-of-band communications or listening to specific routing protocol extensions which carry this information.

FIG. **4** schematically shows elements of the PCEP reply message **103**. The message **103** can comprise: information **104** identifying the path selected by the PCE: information **105** identifying the modulation type selected by the PCE; information **106** identifying the FEC type selected by the PCE; and information **107** identifying the spectrum assignment selected by the PCE. The information **105-107** can be carried as extensions of the PCE Protocol (PCEP). For example, information element **105** can identify a selected value of modulation format by including a numerical code which identifies the modulation format, or by using a binary field where each binary digit represents a different modulation format and a particular one of the digits is set to "**1**" to indicate the modulation format that is selected. Similar techniques can be used to identify the selected FEC type **106**. One exemplary way of indicating the spectrum assignment **107** is described later with reference to FIG. **11**.

An example scenario of operating a WSON will now be described with reference to FIG. **5**. The WSON comprises nodes **1-8**. Intermediate nodes have bandwidth-variable optical cross-connects.

When a path computation request is generated by a PCC (e.g. located at the ingress node **1**), a PCEP PCReq message is received at the IV&RSA PCE **22**. The PCEP PCReq messages identifies the source s and destination d as end points and a requested bit-rate of 100 Gb/s. In addition, the indication of two supported modulation formats is provided: DP-16 QAM and DP-QPSK. These are modulation formats supported by the transponders at nodes **1** and **2**. The IV&RSA PCE **22** computes the set Ps,d of shortest paths given a certain metric (e.g. hop count). A quality of transmission (QoT) metric such as optical signal to noise ratio (OSNR) is also estimated for each path within Ps,d and compared with OSNR threshold values, one per modulation format, such that a bit error rate (BER) of, for example, 10^{-3} is guaranteed (coherent detection and forward error correction (FEC) are considered at the receiver).

In the network of FIG. **5** there are three different possible paths between node **1** and node **2**. The PCE is aware of transmission performance of these paths, such as by using information in the TED **23**. The first path **p1** will experience a received Optical Signal to Noise Ratio (OSNR) of around 33 dB. The second path **p2** has a received OSNR of 26 dB. Finally, the third path **p3** has a received OSNR of 19 dB. These OSNR values are computed accounting for the noise of each link: they represent the OSNR requirements that should be guaranteed.

Different modulation schemes have different requirements. DP-16 QAM halves the required spectrum compared to DP-QPSK, but requires a higher OSNR.

The values of the transmission parameter (e.g. modulation format) are considered. With DP-QPSK modulation at 100 Gb/s, all three paths **p1**, **p2**, **p3** can be successfully set up. In particular, OSNR margins of 16, 9 and 2 dB are experienced for paths **p1**, **p2** and **p3** respectively (w.r.t required OSNR at BER=10^{-3}). With DP-16 QAM modulation at 100 Gb/s,

BER remains below BER=10^{-3} along paths p1 and p2 (with OSNR margins of 9 and 2 dB respectively) while path p3 in this case is unfeasible.

Along path p1, also considering the available margins, DP-16 QAM modulation can be safely configured with half the bandwidth occupation of DP-QPSK.

If a sufficient OSNR margin (with respect to threshold) is present, it is determined if narrow filtering can be applied to further reduce the bandwidth of the signal. The bandwidth can be determined in terms of a required number of frequency slots of a flexible grid. Referring to FIG. **10**, a DP-16 QAM signal can be perfectly handled (no penalties) with a bandwidth of 32 GHz. With a bandwidth of 25 GHz, around 1 dB of penalty is experienced. Considering a particular link, if the difference between the link OSNR and the OSNR threshold is larger than 1 dB, it is possible to apply narrow filtering. In the example just described it is possible to reserve a bandwidth of 25 GHz along the link rather than the theoretically required 32 GHz.

The path requiring the minimum number of frequency slots is selected. The PCE identifies path pl and DP-16 QAM as the optimal path and modulation format, since BER remains below threshold and the occupied spectrum resources are minimised. At this point, the PCE communicates to the PCC using a PCEP PCRep message. This message can identify the selected path by an Explicit Route Object (ERO). The message also includes the selected modulation format and frequency slots. In this example, the message indicates path p1 as the selected path, a value indicating the required spectrum resources, and an indication of DP-16 QAM as the selected modulation format.

Other transmission parameters can be considered by the PCE at the time of path computation. Additional parameters can include FEC type and possibly the optical output power (e.g. which maximises the overall optical reach accounting for OSNR and nonlinear effects). Any additional selected parameters are returned to the PCC in the PCEP PCRep message.

Another scenario will now be described. This scenario is suitable for protection strategies guaranteeing just a percentage of working resources. Flexible transponders enable the transmission of the same modulation format at two given bit-rates. Signals at 200 Gb/s and 100 Gb/s DP-16 QAM are considered. They require different spectrum occupations. In particular, 100 Gb/s DP-16 QAM halves the required spectrum with respect to 200 Gb/s DP-16 QAM. However, the signal at 200 Gb/s is significantly more demanding in terms of OSNR. In this case, a connection request is generated by a PCC **21** and sent as a PCEP Request message to the IV&RSA PCE **22**. The request message indicates source s and destination d as end points and a synchronized path computation request for two different paths. One path corresponds to the working path at a bit-rate of 200 Gb/s while the second one refers to the backup path at a bit-rate of 100 Gb/s. The two path requests are both included within a unique PCEP Synchronized Vector object (SVEC), as specified in RFC 5440. Similarly to the previous scenario, the IV&RSA PCE **22** then computes the set $P_{s,d}$ of shortest paths and related OSNR values such that both working and backup paths meet the requested indications. Finally, the IV&RSA PCE also considers OSNR margins to possibly apply narrow filtering and achieve a further reduction of occupied resources. The result of the joint path computation, achieved by minimizing the overall amount of required frequency slots, is returned to the PCC **21**.

FIG. **6** shows a method performed by a PCC. At step **111** the PCC sends a request to a path computation element (PCE). The request identifies end nodes of the path. Advantageously, the request also identifies **112** a plurality of possible values of at least one transmission parameter supported by the end nodes. For example, if the transmission parameter is modulation format, the request can carry an information element which identifies supported modulation formats. This can be achieved in various ways, such as by using a numerical code to represent a value of a supported modulation format, or by including a binary field where each binary digit represents a different modulation format and a digit is set to "**1**" to indicate the modulation format is supported or set to "**0**" to indicate the modulation format is not supported. At step **113** the PCC receives a reply from the path computation element. The reply identifies a path between the end nodes selected by the path computation element. The reply identifies a selected value of the at least one transmission parameter for the selected path.

FIG. **7** shows a method performed by a PCE. At step **121** the PCE receives a request from the path computation client for computation of a path. The request identifies end nodes of the path. At step **122** the PCE determines a plurality of possible values of a transmission parameter supported by the end nodes. Advantageously, the request received at step **121** identifies the plurality of possible values of the transmission parameter supported by the end nodes and step **122** uses the values received in the request. At step **123** the PCE computes a selected path between the end nodes. Step **123** can include one or more of the additional steps **124**-**127**. At step **124** the PCE finds possible paths between the end nodes. There may be just a single possible path, or a plurality of possible paths. At step **125** the PCE determines a Quality of Transmission metric (e.g. OSNR margin) for each of the plurality of values of the transmission parameter (and for each of the possible paths). This can be performed in two stages. Firstly, the PCE computes an expected OSNR for a path and then compares the OSNR with a target OSNR threshold (to achieve a particular BER, such as 10^{-3}) for each value of the transmission parameter. The amount by which a computed OSNR exceeds a threshold value is an OSNR margin. For example, step **125** can determine an OSNR margin for a DP-QPSK modulation format and an OSNR margin for a DP-16 QAM modulation format. If more than one value of the transmission parameter offers an acceptable quality of transmission metric, or if more than one path offers at least one value of the transmission parameter with an acceptable quality of transmission metric, step **126** selects between possible values of the transmission parameter. An objective function can be used to make the selection. At step **127** the PCE determines if it is possible to apply filtering to reduce the amount of spectral occupation of the signal. Applying filtering will reduce the OSNR margin, as shown in FIG. **10**. At step **128** the PCE sends a reply from the path computation element. The reply identifies a path between the end nodes selected by the path computation element and the reply identifies a selected value of the at least one transmission parameter for the selected path.

The PCE returns both the computed path and the selected modulation format, such that the frequency slot occupation is minimised along the selected path. The PCE has been experimented in a real testbed performing dynamic rerouting with frequency slot assignment and format adaptation from DP-16 QAM to DP-QPSK at 100 Gb/s. FIG. **8** shows an experimental testbed of a flexible WSON with an IV&RSA PCE. The testbed implements DP-QPSK and DP-16 QAM 112 Gb/s (100 Gb/s plus overhead) signal generation through a tunable external cavity laser (ECL) with a line-

width of about 100 KHz, modulated using an integrated LiNbO3 double nested Mach Zehnder modulator. The modulation format can be selected by driving the in-phase (I) and the quadrature (Q) branches of the modulator with a 2-level (QPSK) or a 4-level (16 QAM) electrical signal. The 4-level electrical signal is obtained by adding two 2-level signals with proper delay and amplitudes. The adding operation is performed in the optical domain and a reconfigurable scheme is obtained as depicted in FIG. **8**. In particular, a DFB laser is intensity modulated by a 28 (QPSK) or 14 Gb/s (16 QAM) pseudo random bit sequence (PRBS) of length 211-1, obtained by multiplexing four binary sequences at 3.5 or 7 Gb/s. Two replicas of the optical signal are obtained through a 50/50 splitter, differentially delayed by an integer number of symbol periods (τ_0), and photodetected by a balanced photodetector (adding operation). An optical shutter is also exploited in one of the two splitter arm, in order to generate at the photodetector output a 4-level (shutter off with 3 dB attenuation) or a 2-level (shutter on) electrical signal. The I and Q driving signals are finally obtained by an electrical splitter and differentially delayed by an integer number of symbol periods (τ_e) before being applied to the IQ-modulator. 112 Gb/s DP-QPSK (28 Gbaud) or 112 Gb/s DP-16 QAM (14 Gbaud) transmission is obtained by emulating polarization multiplexing through a 50/50 beam splitter, an optical delay line, and a polarization beam combiner (PBC). The transmitter configuration is performed by controlling the shutter status and the bit pattern generator (BPG) rate.

At the receiver **65**, a coherent detection strategy is applied. Transmitter and receiver are connected through two disjoint paths **71**, **72**. The first (short) path **71** is composed of a 80 km-long standard single mode fiber (SSMF) link, with a received OSNR of 30 dB. The second (long) path **72** comprises three SSMF links, with a total length of 240 km and a received OSNR of 23.2 dB. The nodes consist of four flexible OXCs **73**, each composed of a tunable filter and a MEMS switch. Each OXC **73** is controlled by a mini-PC via a dedicated RS-232 port. The ingress OXC controller also configures the modulation format at the transmitter by properly setting the optical shutter and BPG rate. Similarly, the egress OXC controller sets the proper digital processing strategy (decision rule) for QPSK or 16 QAM format at the receiver. In addition, the OXC controllers can act as PCC running PCEP for path computation requests to the PCE and implement basic RSVP-TE instance, enhanced for slot reservation. In particular, upon Resv message reception, the controller triggers the MEMS switching and tunes the filter according to the lightpath assigned frequency slots.

FIG. **9** shows the testbed performance for the DP-16 QAM and DP-QPSK transmissions. BER vs. OSNR measurements are carried out in back-to-back configuration and along the two possible paths. The OSNR is varied by reducing the optical launch power, and the maximum OSNR values for the short and long link (30 and 23.2 dB, respectively) are indicated as a reference. Results show that, with DP-QPSK, both the short and long paths can be successfully set up. In particular, 13 dB and 6 dB of OSNR margin (w.r.t required OSNR at BER=10^{-3}) are experienced along the short and long path, respectively. On the other hand, with DP-16 QAM, BER remains below 10-3 just along the short path (with a margin of 5.7 dB) while the long path results unfeasible. To show the effect of narrow filtering, FIG. 10 reports the OSNR penalty (with a BER=10^{-3}) experienced for different values of filter bandwidth, i.e. assigned frequency slots of bandwidth 6.25 GHz. Results show that, with DP-16 QAM, no penalty is achieved with at least 5 slots, less than 1 dB with 4 slots, and around 6 dB with just 3 slots. With DPQPSK, no penalty is achieved when at least 9 slots are allocated and a penalty of about 1.5 dB with 6 slots.

A dynamic rerouting experiment is then implemented to show the performance of the PCE architecture. A 100 Gb/s DP-16 QAM connection request was routed along the short path **71**. Then, as upon a short path link disruption, the ingress OXC performs a PCEP request for a restored lightpath. FIG. **11** shows a capture of the PCEP messages exchanged between the ingress OXC (acting as PCC) and the IV&RSA PCE, both implemented in C++. The PCEP session is established through the initial Open and Keepalive messages, then a PCEP Request is submitted to the PCE (packet **13**). The PCE identifies the long path as a candidate for path restoration, however it excludes the DP-16 QAM modulation format due to unacceptable ONSR, while DP-QPSK is selected as the appropriate modulation format, obtaining, as shown in FIG. **7**, a satisfactory OSNR margin of 6 dB. This margin, given the penalties shown in FIG. **10**, is exploited to save three frequency slots along the three links of the long path, i.e. to reduce the amount of required 6.25 GHz frequency slots from a value of 9 to a value of 6. The performed spectrum assignment is first fit and the PCE returns the first 6 adjacent frequency slots. The PCEP Reply message (packet **15**) includes the ERO enclosing the assigned modulation format and FEC and the computed spectrum channel, carried by a Slot Label Object. This object is derived from T. Otani et al, "Generalized Labels for Lambda-Switch-Capable (LSC) Label Switching Routers", RFC 6205, March 2011 and includes a flexible grid specification in addition to the standard CWDM and DWDM ITU-T grids through the definition of two offsets, referred to the lower and the higher slot of the selected spectrum slice, respectively. FIG. **11** shows the object values (Flexible Grid flag, channel spacing 6.25 GHz, lower offset −640, higher offset −635). The object parameters enable the computation of the central frequency and the channel spacing of the assigned frequency slots. In this approach the designated frequency f on the ITU-T frequency grid using a channel spacing fcs and a frequency number n should be interpreted as a spectral slot having a frequency segment between $193.1+(n\pm1/2)f_{cs}$ (THz). An ITU-T frequency number n corresponds to the frequency slot number. Spectral resource allocation can be represented using a number of contiguous frequency slots. The frequency segment with various widths can be specified using parameters of a slot width f_{slot} which is equal to the channel spacing f_{cs}, the lowest frequency slot number n_l, and the highest frequency slot number n_h. Such parameters should be used in the spectral resource labelling in the signalling messages. The centre frequency f_c and the width f_w of the frequency segment are shown as $f_c=193.1+\{(n_l+n_h)/2\}f_{slot}$ (THz) and $f_w=(n_h-n_l+1)\ f_{slot}$(THz).

For the example shown in FIG. **11**:

$n_l=-640$

$n_h=-635$

$f_{slot}=6.25\ \text{GHz}=0.00625\ \text{THz}$

and

$f_c=193.1+\{(n_l+n_h)/2\}f_{slot}\ \text{THz}$

$=193.1+\{(-640-635)/2\}*0.00625$

$=189.115625\ \text{THz}$

and

$$f_w=(n_h-n_l+1)\,f_{slot}\ \text{THz}.$$

$$=(-635+640+1)*0.00625$$

$$=37.5\ \text{GHz}.$$

If control plane signalling is used to set up a path, the returned values can be inserted within the ERO objects of an RSVP Path Message of a subsequent signalling phase. The total IV&RSA PCE computation time is in the order of just 2 ms. A few milliseconds are required for PCEP and signalling communications as well as MEMS switching. Modulation format conversion at the transmitter and receiver is achieved through simple software operations and completed significantly before tunable filter configuration, which requires around 0.5s, in line with other commercially-available flexible OXCs. As an alternative to using the control plane for path set up, the management plane can perform path set up.

A second experiment uses the example WSON shown in FIG. **12**. A protected path between OXC**1** and OXC**2** is requested having just a portion of the working resources guaranteed in the backup path. To this extent, a PCEP Request message is triggered by the NMS encompassing a path request with bit-rate of 200 Gb/s (for the working path) and a second path request at 100 Gb/s (for the back-up path). The bit-rate specification of each path request is enclosed in the PCEP Generalized Bandwidth object described in C. Margaria et al, "PCEP extensions for GMPLS," IETF, draft-ietf-pce-gmpls-pcep-extensions-02, March 2011. The values enclosed in the message are: G.709 OTN traffic spec, OCh signal type at 200 Gb/s and 100 Gb/s, respectively. The two path requests are included in a single PCEP Synchronized Vector (SVEC) object having flags N, L, and S activated. This forces the PCE to jointly compute the two paths by considering as additional constraints the nodes, links and shared risk link groups (SRLG) disjointness. PCE identifies path pl as candidate for the working connection and path p**2** and p**3** as possible candidates for the backup connection. In this experiment, path pl is assumed with available resources and it is selected with the DP-16 QAM modulation format at 200 Gb/s. Among paths p**2** and p**3**, the former (and shorter one) is selected as backup, with DP-16 QAM as the appropriate modulation format at 100 Gb/s. The 2 dB of margin experienced along both paths pl and p**2** may, or may not, be exploited by the IV&RSA PCE to further reduce the overall amount of occupied resources. In this experiment, the PCE maintains the margins to provide additional reliability. The path computation procedure is performed in about 3 ms. Both the working and backup paths are successfully established. As upon failure detection along path p**1**, the pre-reserved backup resources along path p**2** are activated. In this case the activation of the backup path requires adaptation of the bit-rate from 200 Gb/s to 100 Gb/s, both operating with DP-16 QAM. Such adaptation is successfully performed using software operations at the transmitter and receiver.

FIG. **13** shows an exemplary processing apparatus **80** which may be implemented as any form of a computing and/or electronic device, and in which embodiments of the system and methods described above may be implemented. In particular, an instance of device **80** may be used to implement the PCC and an instance of device **80** may be used to implement the PCE. Processing apparatus **80** comprises one or more processors **81** which may be microprocessors, controllers or any other suitable type of processors for executing instructions to control the operation of the device. The processor **81** is connected to other components of the device via one or more buses **86**. The processor-executable instructions **83** may be provided using any computer-readable media, such as memory **82**. The memory is of any suitable type such as read-only memory (ROM), random access memory (RAM), a storage device of any type such as a magnetic or optical storage device. Additional memory **84** can be provided to store data **85** used by the processor **81**. The processing apparatus **80** comprises one or more network interface inputs **88** for interfacing with other network entities. The processing apparatus **80** can also comprise one or more input interfaces for receiving input from a user.

Modifications and other embodiments of the disclosed invention will come to mind to one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of this disclosure. Although specific terms may be employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

The invention claimed is:

1. A method for servicing a request for path computation at a path computation element in a wavelength switched optical network, the method comprising:

receiving a request from a path computation client for computation of a path between end nodes, the request identifying the end nodes and a transmission parameter that is supported by the end nodes, the transmission parameter including a bit rate and a plurality of modulation formats;

determining a plurality of values of the transmission parameter supported by the end nodes;

computing one or more paths between the end nodes for the transmission parameter based on meeting a bit error rate (BER) below a set threshold, wherein the computing further comprises selecting one of the values of the transmission parameter that provides the path requiring a minimum number of frequency slots from the one or more paths computed; and

sending a reply to the path computation client, wherein the reply identifies the path computed between the end nodes and the reply identifies the selected value of the transmission parameter for the computed path.

2. The method according to claim **1**, wherein the determining the plurality of values of the transmission parameter supported by the end nodes comprises using the plurality of values of the transmission parameter.

3. The method according to claim **1**, wherein computing the one or more paths between the end nodes comprises:

computing a quality of transmission metric for each of the plurality of values of the transmission parameter; and

selecting one of the values of the transmission parameter on a basis of the computed metrics.

4. The method according to claim **3**, wherein computing the quality of transmission metric is performed for a plurality of possible paths between the end nodes, and wherein selecting one of the values of the transmission parameter is performed for the metrics obtained for the plurality of possible paths.

5. The method according to claim **3**, wherein selecting one of the values of the transmission parameter is performed for minimization of bandwidth and a quality of transmission metric exceeding a target threshold value.

6. The method according to claim 3, wherein the quality of transmission metric is an optical signal to noise ratio margin.

7. The method according to claim 1, further comprising determining if filtering can be applied to reduce bandwidth along the path.

8. A method of requesting computation of a path at a path computation client in a wavelength switched optical network, the method comprising:

sending a request to a path computation element for computation of a path between end nodes, the request identifying the end nodes and a transmission parameter that is supported by the end nodes, the transmission parameter including a bit rate and a plurality of modulation formats; and

receiving a reply from the path computation element, wherein the reply is based on the path computation element determining a plurality of values of the transmission parameter supported by the end nodes, the path computation element computing one or more paths between the end nodes for the transmission parameter based on meeting a bit error rate (BER) below a set threshold, and the path computation element selecting one of the values of the transmission parameter that provides the path requiring a minimum number of slots from the one or more paths, wherein the reply identifies the path between the end nodes computed by the path computation element, and the reply identifies the selected value of the transmission parameter for the path.

9. The method according to claim 8, wherein the transmission parameter also includes

a Forward Error Correction type.

10. The method according to claim 8, wherein the reply comprises a spectrum assignment for the path.

11. The method according to claim 8, wherein the reply comprises a Path Computation Element Communication Protocol reply message comprising an element which identifies the selected value of the transmission parameter.

12. A path computation element for use in a wavelength switched optical network, the path computation element comprising:

an interface for communicating with a path computation client; and

a processor configured to:

receive a request from the path computation client via the interface for computation of a path between end nodes, the request identifying the end nodes and a transmission parameter that is supported by the end nodes, the transmission parameter including a bit rate and a plurality of modulation formats,

determine a plurality of values of the transmission parameter supported by the end nodes,

compute one or more paths between the end nodes for the transmission parameter based on meeting a bit error rate (BER) below a set threshold, wherein the computing of the path further comprises selecting one of the values of the transmission parameter that provides the path requiring a minimum number of frequency slots from the one or more paths computed, and

send a reply via the interface, wherein the reply identifies the path computed between the end nodes selected by the path computation element, and the reply identifies the selected value of the transmission parameter for the path.

13. A path computation client for use in a wavelength switched optical network, the path computation client comprising:

an interface for communicating with a path computation element; and

a processor configured to:

send a request for computation of a path to the path computation element via the interface, the request identifying end nodes of the path and a transmission parameter that is supported by the end nodes, the transmission parameter including a bit rate and a plurality of modulation formats, and

receive a reply from the path computation element, wherein the reply is based on the path computation element determining a plurality of values for the transmission parameter supported by the end nodes, the path computation element computing one or more paths between the end nodes for the transmission parameter based on meeting a bit error rate (BER) below a set threshold, and the path computation element selecting one of the values of the transmission parameter that provides the path requiring a minimum number of slots, wherein the reply identifies the path between the end nodes computed by the path computation element, and the reply identifies the selected value of the transmission parameter for the path.

14. A non-transitory machine-readable medium having instructions stored therein, which when executed by a processor, cause a path computation element to perform operations comprising:

receiving a request from a path computation client for computation of a path between end nodes, the request identifying the end nodes and a transmission parameter that is supported by the end nodes, the transmission parameter including a bit rate and a plurality of modulation formats;

determining a plurality of values of the transmission parameter supported by the end nodes;

computing one or more paths between the end nodes for the transmission parameter based on meeting a bit error rate (BER) below a set threshold, wherein the computing further comprises selecting one of the values of the transmission parameter that provides the path requiring a minimum number of frequency slots from the one or more paths computed; and

sending a reply to the path computation client, wherein the reply identifies the path computed between the end nodes and the reply identifies the selected value of the transmission parameter for the computed path.

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